A Taxonomy of Potential Cooperative Human/Robotic Roles in Extravehicular Operations

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Abstract

This paper proposes the establishment of a taxonomy of potential interaction levels between humans and robots in the extravehicular work site:

- Robotic assistant
- Robotic associate
- Robotic surrogate
- Robotic specialist
- Human/robotic symbiosis

The first three categories deal with increasing levels of robotic capability to perform EVA tasks, particularly using EVA (rather than specialized robotic) interfaces. "Specialist" activities refer to specific task assignments that are singularly associated with humans or robots, such as an Astronaut Support Vehicle or a Telerobotic Rescue System for EVA. The last category refers to robotics technology in intimate contact with the extravehicular human, such as a robotically-augmented space suit. Examples of each of these will be detailed from past experiments in neutral buoyancy and space, and plans presented for future applications which will expand the boundaries of human/robotic interactions in space.

Overview

[Author's note: Numerous graphics exist for most of the concepts detailed herein, and the paper would convey information much more clearly and accurately if they were used. In order to meet the restrictive size limits, while providing a minimal degree of graphics on the required summary page, almost all of the figures in this document have had to be deleted. With the capabilities of modern high-speed internet access, NASA might want to reconsider the burdensome degree of file size restriction applied to this call for similar events in the future.]

Historically, robots and humans in space were discussed only in terms of mutual exclusivity. If human spaceflight were involved, clearly any external activities would be performed by astronauts in pressure suits. If a mission did not include humans, then external activities… would probably be designed out of the mission. Although discussions would be overheard about "humans versus robots", they would more properly have been titled "human versus automated space flight".

With the advent of extensive on-orbit activities associated with operations of the International Space Station (ISS), there has been some meaningful incorporation of robotics into planning cycles. Indeed, one glance at the requirements for EVA in the upcoming decade shows annual EVA hours comparable to the cumulative total EVA hours in all the decades of human space flight up until this time. This trend will only continue to grow in the future. A single human Mars mission could easily increase the cumulative total EVA time by an order of magnitude or more. Despite the known near-term and anticipated far-term requirements for space operations, very little meaningful attention has been paid to the concept of integrating human EVA and robotics in the same work site, in a truly cooperative endeavor. It is the underlying thesis of this white paper that the most productive form of external operations in space, whether in orbit or on planetary surfaces, will come from a well-designed cooperation between astronauts and robots.

In discussing cooperative roles for humans and robots in space, it is important to first address the question of what is meant by the term “robot”. Since the early days of the space program, unmanned satellites have been referred to as “robotic”, particularly deep-space probes. This would lead to the concept that any inanimate object is a “robot”, and the pressure suit itself would be a prime (and essential!) example of human/robotic interaction.

For the purposes of this discussion, “robotics” will be restricted to systems which can interact with, and modify, the local environment. This would clearly include the classical concept of a system with manipulators, but also includes systems capable of providing controllable mobility, whether only for itself or also for other systems. Thus, a camera mounted on either a free-flying platform in space or a wheeled mobility unit on a planetary surface is a robot, even if not supplied with means of manipulation.

It is also important to explicitly detail what is meant by cooperation. One might, for example, suggest that the Lunar Surveyor program was a cooperative effort with the Apollo program. While Surveyor provided a knowledge base on lunar surface conditions, the data return from Surveyor did not directly affect the planned Apollo surface operations. For the purposes of this discussion, “cooperation” will be limited to support (in physical or data terms) of real-time utility in astronaut operations. For example, while the Lunar Orbiter program provided mapping that established the landing and science sites on the moon, the data was all used in the planning phase. A system which provides immediate localization of crew position would be included, but a large-scale mapping system would not under this definition.

One of the most significant choices in examining this field is in the categorization of cooperative activities. Since the range of potential human activities in space (which will be drawn from both orbital operations and planetary surface exploration) is so great, dealing with cooperation on a case-by-case basis would be futile. Neither would it make sense to break cooperation down into details of what task is being performed (manipulation, mobility, etc.) as many implementations of cooperation will entail the combination of several of these categories.

The one common metric running throughout all of the candidate space activities under consideration is the skill set of the human component. By comparing the skills asked of the robotic participant to those brought to the work site by the human, it is possible to develop a taxonomy based roughly on the complexity (or capabilities) of the robotic system. Extending the analogy further to regarding the robots as “humans in training”, the following categories have been defined:

Assistant – Like a human apprentice, robots at this level accomplish simple and limited tasks performed under direct control and supervision of the human.

Associate – Analogous to a journeyman, a robotic associate is capable of more complex tasks and greater levels of autonomy, although still under human supervision.

Surrogate – Just as the top level of human skills was regarded as a master craftsman, a robotic surrogate should be capable of any tasks which might be performed by an EVA human, without direct control and with only minimal supervision.

Specialist – Whereas a surrogate (or master) level of skills connotes general prowess, there will always be some tasks best performed by a specialist. This might be thought of as equivalent skill and performance level to the robotic surrogate, but over a much more limited task set.

Symbiote – The one category developed here without analogy to apprenticeship training, this area refers to blending human and robotic capabilities so integrally together that the human performance is directly affected (ideally, augmented) by the robotic systems.

All of these categories will be further explained and illustrated by examples throughout the rest of this paper.

Robotic Assistant

Like a new apprentice, the robotic assistant supports the EVA crew in performing the specified operations. Typically, all dexterous operations are performed by EVA: the robotic assistant performs limited (frequently single) actions in support of the humans.

Perhaps the most well-known of EVA assistants would be the Space Shuttle Remote Manipulator System (RMS). The RMS is valued in EVA planning as a positioning and restraint system for the EVA crew. This relieves the need for the crew to install and adjust portable foot restraints at the work site, as many of these tasks can be accomplished by the RMS degrees of freedom. One might also categorize RMS capture and positioning of large masses as an assistant's task; even if the RMS is manipulating a mass beyond the capacity of the humans, the dexterous servicing operations are all performed by the human on the site.

The planetary surface equivalent of RMS mobility would be an EVA transportation system, such as the Lunar Roving Vehicle from the later stages of the Apollo Program. While it may seem strange to take what is universally recognizable as a car and call it a robot, it provides exactly the same degree of augmented human mobility as provided by the RMS on-orbit.

Beyond mobility, robotic assistants can augment the utility and safety of EVA operations by providing an observation point for use by IVA crew or ground controllers. The University of Maryland Space Systems Laboratory (SSL) has developed the Supplemental Camera And Mobility Platform, or SCAMP vehicle, to provide a remotely controllable camera viewpoint in neutral buoyancy simulation of EVA and robotic operations. SCAMP is a roughly spherical vehicle with symmetrical ducted fans for propulsion, carrying a single color video camera. This vehicle has been used extensively throughout the last seven years, supporting tests at every neutral buoyancy facility in the US, including EVA crew training at the NASA Johnson Space Center Weightless Environment Training Facility. A similar system was developed by the NASA Johnson Space Center and tested in space on STS-87 in 1997.

In future space operations, the observation function will become increasingly important for a variety of reasons. Already, EVAs on the International Space Station are in location where there is minimal or no coverage from fixed cameras, and it is difficult for observers (either on board or on the ground) to maintain situational awareness. Since public engagement is the linchpin of future ambitious space missions such as manned Mars exploration, it will be essential to provide sufficient quality and quantity of video coverage to give the "customers" (the taxpaying public) the virtual experience of accompanying the astronauts on their mission. Whether in space or on the surface of a planet, these observational assistants will be an integral part of future work sites.

For EVA observations in the planetary surface environment, one might again look to the Lunar Roving Vehicle. Once the LRV stopped at a work site and the astronauts had manually aligned the high-gain antenna with Earth, a ground-controlled color video camera was used to follow the crew activities at each site. For future planetary surface activities, while similar cameras will probably be mounted on crew mobility systems, one might also envision microrovers similar to the Pathfinder Sojourner rover with augmented velocity capabilities, programmed to follow individual EVA crew in surface activities and provide video coverage of their operations to the planetary base camp and back to Earth.

Although the focus of this white paper is specifically EVA, it is important to point out that all of these systems have parallels in internal, or IVA, operations. For example, the SSL is in the process of designing a microSCAMP vehicle for IVA monitoring. The size of a softball, μSCAMP will be programmed to follow an individual in the International Space Station, and will provide a real-time "over the shoulder" view of the specific task being performed by the IVA astronaut. By providing audio microphones and a speaker, the μSCAMP can become the "eyes and ears" of a scientific researcher on the ground. The flight crew can interact with the surface scientist directly through the mechanism of μSCAMP, providing a "telepresence" for the remote scientist on-board the International Space Station.

Although all of the examples to date of robotic assistants have been limited to peripheral activities (mobility and/or observation), there is no reason to limit the category to those tasks. In 1989, the SSL performed a series of Hubble Space Telescope servicing tasks using the Beam Assembly Teleoperator (BAT). Designed specifically for teleoperated assembly of the EASE space structure, BAT was never intended for satellite servicing activities. Although it was used to attempt pure telerobotic servicing of HST, a more productive simulation used BAT as a robotic assistant to a pressure-suited human. In this mode, BAT usefully transported tools and orbital replacement units (ORUs) from storage locations to the work site, minimizing human time spent on translating and transporting equipment, and maximizing human time spent in repair activities. An earlier SSL vehicle, the Apparatus for Space TeleRobotic Operations (ASTRO), was used to transport structural components to an EVA subject performing structural assembly operations.

Robotic Associate

The associate, or "journeyman" level of competence, implies a greater degree of skill and reliability than was present in the assistant. For example, an associate might be responsible for work site preparation and completion, just as a surgical resident might open and close a patient for a senior surgeon performing the specific operation. In illustration of this approach, the SSL Ranger Neutral Buoyancy Vehicle (NBV) was used in further HST testing as a robotic associate for the EVA human. Equipped with two dexterous arms and interchangeable end effectors, Ranger was positioned by an underwater version of the RMS to prepare a Hubble Space Telescope mock-up for servicing. Ranger released the latches and opened the door covering the equipment bay, and installed foot restraints for the EVA crew. After the human removed the ORU, Ranger exchanged it for a new one, and took the old ORU to a storage site and stowed it. After the new ORU was in place, the human left the area, and Ranger closed out the bay and cleaned up the work site. In this case, the robotic system performed the repetitive and nonproductive support tasks that would have take a majority of the human's time had they been performed manually.

Robotic associate tasks for planetary surface activities will include helping the EVA crew in exploratory activities. In the majority of cases, these activities will resemble geological field studies on earth. While the human on-site will be essential for recognizing fine detail and directing sampling, it would be useful to have a system capable of procuring rock samples and storing them for later analysis. Further, one of the most interesting geological sites is always a vertical cliff face, which exposes samples of different geological eras in a single location. It is unlikely that EVA operations in the foreseeable future will be extended to repelling and climbing vertical surfaces in search of ideal rock samples. Therefore, some capacity for extreme vertical reach would be very useful in such a vehicle.

The SSL has performed the conceptual design of a robotic associate for planetary surface science operations. This vehicle would provide a mobility base for a dexterous manipulator pair and stereo vision system, mounted on a large positioning manipulator incorporating both rotary and extension elements, resulting in reach capabilities as much as 10 meters up or down a vertical cliff face. The size of the mobility unit is based on ability to traverse 99th percentile Martian terrain; the manipulator system is sized to perform human-scale tasks.

It would be worthwhile to take a moment to discuss the issue of physical size in operational robotics, whether for planetary surface or in-orbit applications. There has been a highly productive tendency in past years to reduce the size of spacecraft and of robotic systems. The Sojourner rover on the Mars Pathfinder experiment would not have been possible with more traditional, Titan-class payload thinking from past years. At the same time, it is important not to be too intoxicated with the success of “smaller, faster, cheaper” and thereby to believe that everything can be accomplished with systems weighing a few kilograms. At the levels of robotic associates and surrogates, the generic requirement is that the systems be capable of performing tasks currently performed by humans. This requires human-scale strength, and speed, and reach, which in term requires human scales in physical components. As will be discussed in the conclusion, the optimum system will include a number of robots at all skill levels and in many different physical sizes, to most effectively perform the required space operations.

Robotic Surrogate

A robotic surrogate is a robot that can accomplish any task capable of operation by a human in a pressure suit. Implicit in this is a requirement that the robotic system use the human interfaces, rather than specialized robotic interfaces. One of the major advantages of humans in space flight is their ability to adapt to perform contingency and emergency operations. That same skill mix must be present in the robotic system to deserve the title of “surrogate”.

An interesting dichotomy of opinion exists on the effective way of providing human-equivalent capabilities with EVA-compatible interfaces. One approach, adopted by the SSL, is that nonanthropomorphic systems can be used to provide high-level skills, through the adoption of expedient schemes such as interchangeable end effectors to account for a lack of truly dexterous end effectors. The Ranger vehicle was developed based on this design philosophy, and on the experience of telerobotic structural assembly and satellite servicing in neutral buoyancy gained over the past two decades by the SSL. Ranger incorporates two 8 degree-of-freedom (DOF) dexterous manipulators, incorporating interchangeable end effectors that represent the robotic equivalent of the EVA tool kit. A 6 DOF grapple arm attaches Ranger to the work site and provides local positioning, and a 7 DOF manipulator carries a stereo camera pair to allow a wide range of camera views with minimal duplication of cameras. Ranger NBV has been tested in neutral buoyancy on structural assembly and HST and ISS servicing tests, both singly and in cooperation with EVA subjects. The Ranger Telerobotic Shuttle Experiment (TSX) is a space flight validation of Ranger operational experience, which is planned for a shuttle flight in late 2003.

The alternative design philosophy for surrogate-class robotics moves the design interface from the tool grip to the ORU handle, and requires across-the-board adherence to anthropomorphic design. Under active development by the NASA Johnson Space Center, the Robonaut concept is a highly anthropomorphic robot, down to five-fingered human-type hands. Robonaut is designed to use existing EVA tools, and to be capable of all current EVA tasks, including highly dexterous tasks such as manipulating EVA tether hooks. The Robonaut prototype is currently being tested in a laboratory setting.

Either of these concepts could be extended to planetary surface operations. Robotic manipulators (similar to those on either

Ranger or Robonaut) could be mounted on a mobility vehicle to perform autonomous or teleoperated surface science, and to accompany an EVA crew on an surface exploration mission. Student projects at the University of Maryland have performed the detailed design of such vehicles, including the capability to provide a "ride-on" capability for astronauts, either in baseline operations or (for the smaller vehicles) as a contingency to effect an astronaut rescue. This rescue capability is significantly augmented by the provision of local manipulation, as the robot arms can be used to retrieve and secure the incapacitated astronaut for the return trip.

It is important to point out that the (eventual) existence of robotic systems "as capable as an EVA astronaut" does not in any manner presage the demise of human space flight. The most important thing about robotic surrogates is that it provides a useful choice – a task which might have demanded a human EVA could be performed by a robotic system. Alternatively, a task which would normally be performed by a robot might be accomplished EVA, if that proved to be more convenient. While the "surrogate" label encompasses the skills and dexterity of the robot, it does not require that the performance be equivalent. Indeed, it is likely that the first generations of robotic surrogates will be considerably slower at any given task than a human, but still useful in relieving the demand on limited EVA time.

Robotic Specialist

Despite the skill of a master craftsman, there will always be tasks for which the proper response is to call in a specialist. So too in space, some categories of activities will call for specialized robotic systems to perform the tasks.

One such category is that of robotic "lifeguard". As far back as 1987, the SSL used BAT to demonstrate the use of a free-flying manipulative robot to perform the rescue of a simulated incapacitated human in a space suit. During these tests, BAT investigated a number of means of safely grasping and controlling the pressure suit, then free-flying with the subject to the Space Shuttle airlock hatch. NASA JSC envisioned similar applications for its EVA Retriever development, which was baselined as an autonomous system (rather than teleoperated as BAT was), although it never proceeded to the stage of testing with pressure suits.

Another specialist concept is that of an Astronaut Support Vehicle, or ASV. Directly analogous to the diver support vehicles used in undersea operations, an ASV would provide a pressurized cabin to support the humans in extended missions beyond the ISS, then support them for in-situ EVA operations to perform the required task, such as satellite servicing. One approach to an ASV was demonstrated by the SSL with the use of the Multimode Proximity Operations Device (MPOD). For this application an EVA foot restraint was mounted to the front of MPOD, which stabilized the EVA subject and provided mobility (and, conceptually, life support functions) during HST repair activities. This early test demonstrated feasibility, and raised a number of interesting research questions regarding displays and controls for the EVA subject, means and modes of interacting with the robot, and so forth.

The planetary surface equivalent of the ASV is the pressurized rover. This category of vehicle would provide comfortable life support conditions and mobility for an extended traverse, supporting exploratory EVAs along the way. Most conceptual designs also incorporate manipulators, so that some surface activities could be performed without the need to suit up and egress the vehicle. One design activity performed by a student design project at the University of Maryland demonstrated the potential to design such a system to function for 70 day traverses, with 3500-4000 km round-trip travel distances supporting several weeks of scientific studies enroute. A second such design project proved the feasibility of a solar-powered rover to circumnavigate the moon at the equator in a single lunar daylight period.

Human/Robot Symbiote

This category moves beyond all of the others, in which humans in current technology pressure suits interact with various robotic systems, to ask how robotic technology can be adapted to directly augment the human. Subsumed in this category are advanced suit concepts, such as highly instrumented suits, or suits modified to augment control and display capabilities.

Beyond knowledge transfer, robotic technology might be co-located with the pressure suit. The Dexterous Manned Maneuvering Unit is a concept which incorporates dexterous manipulators into a free-flight mobility unit. The hand controllers of the mobility unit would be switched between modes to also control manipulator motion. Such a system could be used for delicate assembly activities that exceed baseline EVA capabilities but need human vision on-site, such as berthing large modules to ISS. In a more mundane operation, the manipulators could be used to provide crew restraints in areas not originally intended for EVA access, or to carry payloads while free-flying.

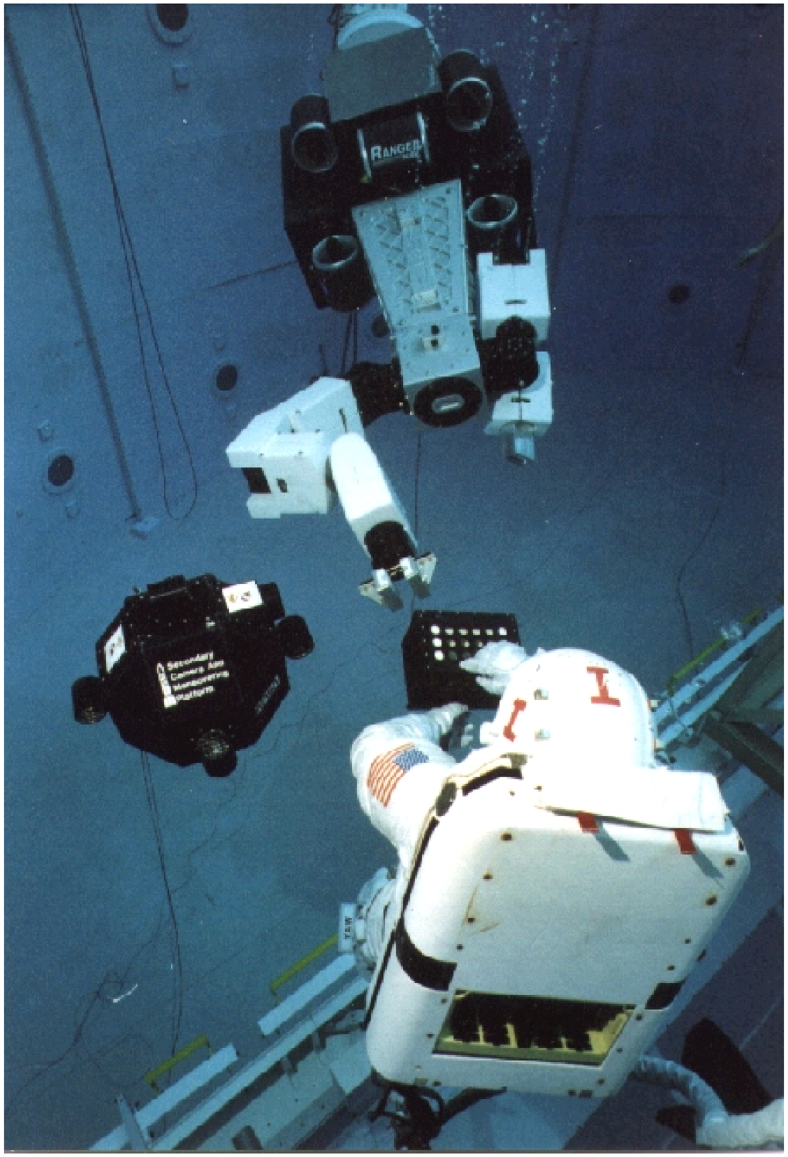
One further step away from the classic pressure suit is the concept of a Manned Autonomous Work System. This concept (perhaps better known colloquially as "man-in-a-can") removes the requirements for complex articulations in the lower body of the suit, and provides a shirtsleeve environment for the human as a co-located manipulator controller. Other concepts for MAWS include articulated pressure suit-type arms, to provide the human with the means of getting "hands-on" with the task hardware. Such a system could eliminate the atmosphere loss associated with airlocks, eliminate prebreathe requirements, and provide the capability of adding shielding for operations in regions of space with greater micrometeoroid or radiation flux.

Perhaps the ultimate goal of the concept of human/robotic symbiosis is the powered suit. Experimental data from the Experimental Assembly of Structures in EVA (EASE) program in the mid-1980's indicated that approximately 75% of the astronauts' externally focused efforts (that is, metabolic energy above than needed to maintain life functions) went into moving the joints of the pressure suit. This leads to fatigue, and severely limits the extent to which EVA can be used. Current technology developments in the SSL have demonstrated the ability to robotically augment the metacarpophalangeal (MCP) joint of the hand, to provide articulation at a place in the pressure suit glove which has never been available in an operational unit. This technology demonstrated a 16:1 reduction in required force to actuate the MCP joint, which brings that joint of the glove down to nearly nude hand performance. With foreseeable advances in actuator and sensor technology, robotic power assistance could be extended to all of the joints of a pressure suit, with the aim of reducing the operator workload to merely that necessary to sense intended motions, with the suit supplying all remaining required forces and torques. Initially this technology will be used to just eliminate suit torques; ultimately it might be used in a "human amplifier" mode to greatly increase the capabilities of an EVA human. Use of such a powered suit system would allow the astronaut to safely manipulate masses and inertias far beyond those currently handled, and might allow more frequent EVAs due to much lower crew fatigue. Indeed, as an ultimate example, such a suit might detect the incapacitation of its wearer in planetary surface exploration, and autonomously get up and walk back to the base airlock without any inputs from the wearer. Such a "self-rescuing" suit would provide the ultimate in safety for human planetary exploration.

Conclusions

It is extremely important to point out that truly productive use of robots in an integrated work site need not pertain to only one robot, or only one level of robotic interaction. Throughout the Ranger/EVA HST servicing described above, SCAMP provided an exterior view of the work site, which was as important for controlling Ranger as it was for monitoring the EVA. After removal of the ORU, SCAMP moved into the equipment bay and did a detailed survey of the site before the replacement unit was installed. Following door closure SCAMP inspected the latches, and identified the one which had been intentionally done incorrectly. Just as it is a waste to use an astronaut in an apprentice-level task, so it may be more productive to use assistant robots to perform assistant tasks, freeing up associate or higher level robots for their more complex tasks. The truly cooperative worksite of the future will most likely contain several EVA humans and many robots, operating effectively and cooperatively at all levels of activity.

Future Cooperative Work Sites



- Assistants – Humans perform primary tasks
- Associates – Humans perform selected tasks
- Surrogates – Humans perform limited or no direct tasks
- Specialists – Humans and robots fill unique niches (e.g., astronaut support vehicle)
- Symbiosis – Robotic systems in direct contact with humans (e.g., powered suit)